NASA Technical Memorandum 110286

Properties of Two Carbon Composite Materials Using LTM25 Epoxy Resin

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November 1996

National Aeronautics and
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Summary

In this report, the properties of two carbon-epoxy prepreg materials are presented. The epoxy resin used in these two materials can yield lower manufacturing costs due to its low initial cure temperature, and the capability of being cured using vacuum pressure only. The two materials selected for this study are MR50/LTM25, and CFS003/LTM25 with Amoco T300 fiber; both prepregs are manufactured by *The Advanced Composites Group*†. MR50/LTM25 is a unidirectional prepreg tape using Mitsubishi MR50 carbon fiber impregnated with LTM25 epoxy resin. CFS003/LTM25 is a 2 by 2 twill fabric using Amoco T300 fiber and impregnated with LTM25 epoxy resin. Among the properties presented in this report are strength, stiffness, bolt bearing, and damage tolerance. Many of these properties were obtained at three environmental conditions: cold temperature/dry (CTD), room temperature/dry (RTD), and elevated temperature/wet (ETW). A few properties were obtained at room temperature/wet (RTW) and elevated temperature/dry (ETD) conditions. The cold and elevated temperatures used for testing were -125°F and 180°F, respectively. In addition, several properties related to processing are presented.

Symbols

E_1^c	longitudinal modulus, compression
E_2^c	transverse modulus, compression
E_1^t	longitudinal modulus, tension
E_2^t	transverse modulus, tension
F_p^{br}	bolt bearing proportional limit stress
F_u^{br}	bolt bearing ultimate stress
F_y^{br}	bolt bearing yield stress
F_u^{cai}	compression-after-impact ultimate stress
F_1^{cu}	longitudinal ultimate stress, compression
F_2^{cu}	transverse ultimate stress, compression
F_u^{ohc}	open-hole compression ultimate stress
F_u^{oht}	open-hole tension ultimate stress
F_{12}^{su}	in-plane shear ultimate stress

† The use of trademarks or names of manufacturers in this report is for accurate reporting and does not constitute an official endorsement, either expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

F_1^{tu}	longitudinal ultimate stress, tension
F_2^{tu}	transverse ultimate stress, tension
G_{12}^{s}	in-plane shear modulus
M_g	moisture gain from the dry to the wet condition
T_g	glass transition temperature
T_g^{dry}	glass transition temperature, dry
T_g^{wet}	glass transition temperature, wet
t_{nom}	nominal ply thickness
V_f	fiber volume fraction
α_1	longitudinal coefficient of thermal expansion at room temperature
α_2	transverse coefficient of thermal expansion at room temperature
γ_{12}^{su}	in-plane ultimate strain
ε_u^{cai}	compression-after-impact ultimate strain
ε_1^{cu}	longitudinal ultimate strain, compression
ε_2^{cu}	transverse ultimate strain, compression
ε_1^{tu}	longitudinal ultimate strain, tension
ε_2^{tu}	transverse ultimate strain, tension
ν_{12}^{c}	major Poisson's ratio, compression
ν_{12}^{t}	major Poisson's ratio, tension
ν_{21}^{c}	minor Poisson's ratio, compression
ν_{21}^{t}	minor Poisson's ratio, tension
ρ	material density

<u>Superscripts</u>

br	bolt bearing
c	compression
cai	compression-after-impact
cu	compression ultimate
dry	dry condition
ohc	open-hole compression
oht	open-hole tension
s	shear
su	shear ultimate
t	tension
tu	tensile ultimate
wet	wet condition

Subscripts

f	fiber
g	glass transition
nom	nominal
1	longitudinal
12	shear
2	transverse

Acronyms

CAI	compression-after-impact
CTD	cold temperature/dry
ETD	elevated temperature/dry
ETW	elevated temperature/wet
OHC	open-hole compression
OHT	open-hole tension
RTD	room temperature/dry
RTW	room temperature/wet

1.0 Introduction

New resin systems are being introduced which offer the possibility of reducing the manufacturing costs of composite materials. These resin systems can be cured at relatively low temperatures (typically less than 200°F), followed by a post-cure at a higher temperature. This post-cure increases the composite's glass transition temperature, T_g. If the composite part is properly supported, the post-cure procedure can take place after the composite part has been removed from the tool[†]. Such resin systems can lower manufacturing costs by reducing demands on the temperature capability of the tooling; if the composite part is to undergo a free-standing post-cure, the tooling does not have to withstand the post-cure temperature, only the lower initial cure temperature. Tools for lower temperature applications are typically less expensive. Besides lowering tooling costs, a resin system with these characteristics

[†] However, a free-standing post-cure is not necessary. If the tooling is capable of withstanding the post-cure temperature, it is possible to post-cure the composite while still in the tool.

can minimize problems related to mismatched coefficients of thermal expansion between the tooling and the composite part. Since the tool and the composite part only need to be in contact during the initial lower-temperature cure, the dimensional difference between the tool and the part is minimized. For some applications, the material properties obtained from the initial cure, without the subsequent post-cure, are sufficient. In addition, many of these materials can be cured under vacuum pressure only, eliminating the need for an autoclave, and further reducing manufacturing costs.

There is little information on the properties of composites that use these new resin systems. In reference 1, the properties of composites using some of these resins with fiberglass reinforcements are investigated. However, no data is presented for composites using carbon fibers. In many applications carbon fibers are a necessity due to the performance requirements of the aircraft. In this report, the properties of two carbon-epoxy prepregs using one of these new epoxy resins, are presented.

The two materials selected for this study are MR50/LTM25, and CFS003/LTM25 with Amoco T300 fiber; both prepregs are manufactured by *The Advanced Composites Group*. MR50/LTM25 is a unidirectional prepreg tape using Mitsubishi MR50 carbon fiber impregnated with LTM25 epoxy resin. CFS003/LTM25 is a 2 by 2 twill fabric using Amoco T300 fiber and impregnated with LTM25 epoxy resin. The LTM25 resin can use initial cure temperatures from 125 to 210°F. Initial cure time-temperature combinations range from 12 hours at 125°F to 0.35 hours at 210°F. A two hour post-cure at 250°F is recommended to obtain the best properties. Curing pressure may be applied through autoclave, vacuum bag, or press molding. These prepregs were provided as net-resin systems; no bleeding during curing was required or recommended.

The properties obtained for these two materials are listed in Tables 1, 2, and 3. Many of these properties were obtained at three environmental conditions: cold temperature/dry (CTD), room temperature/dry (RTD), and elevated temperature/wet (ETW). A few properties were obtained at room temperature/wet (RTW) and elevated temperature/dry (ETD) conditions. The cold and elevated temperatures used for testing were -125°F and 180°F, respectively. (The cold temperature of -125°F was determined by the requirements of very high altitude aircraft.) In addition, several properties related to processing are presented.

All the composite laminate manufacturing was performed at Northrop Grumman Corporation. Specimen manufacturing and testing was performed at Northrop Grumman

Corp. and NASA Langley Research Center (LaRC). All the work performed at Northrop Grumman Corp. was done under NASA contract NAS1-19347. The data presented in this report is a summary of the results presented in references 2 and 3 (NASA Contractor Reports prepared by Northrop Grumman Corp.), and additional results from tests performed at NASA Langley Research Center. More details on the testing and experimental results can be found in references 2 and 3. The purpose of this report is to summarize all the available results under one cover. This work was sponsored by NASA's Environmental Research Aircraft and Sensor Technology (ERAST) program.

Readers are advised that the results presented in this report were obtained from a limited number of tests and are intended to be used for material evaluation purposes. These results must not be considered to be material allowable values.

2.0 Manufacturing

All laminates used in this study were manufactured by Northrop Grumman Corporation using the following procedure:

Debulking

1) Debulk the layup after every fourth layer under vacuum of no less than 25 inches of mercury for 15 minutes.

Curing

1) Apply vacuum of no less than 25 inches of mercury.
2) Increase temperature at the rate of 1°F/minute.
3) Hold temperature at 150°F for 9.5 hours.
4) Cool laminate under vacuum at a rate of 2°F/minute.
5) Release vacuum.

Post-curing

1) Increase temperature at the rate of 2°F/minute.
2) Hold temperature at 250°F for 2 hours.
3) Cool laminate at a rate of 6°F/minute until temperature has been lowered to at least 140°F.

The laminate bagging layout used is shown in Figure 1. Since the prepreg materials used were net-resin systems, bleeding of the laminates during cure was avoided. The personnel performing the manufacturing noted that these prepregs exhibited unusually aggressive tack. Leaving the prepreg materials at room temperature for 24 hours reduced the tack, and made the layup process easier.

Additional laminates of both prepregs were manufactured solely to assess an alternate debulking procedure (the curing and post-curing procedures remained as defined above). In this alternate debulking procedure, the layup was debulked every 24 layers under vacuum of no less than 25 inches of mercury for one hour. No significant differences in the ultrasonic inspection results or the void volume content were found between laminates manufactured by the two debulking procedures.

3.0 Inspection

All laminates were ultrasonically inspected by Northrop Grumman Corporation. This inspection revealed significant amounts of porosity in laminates manufactured from both prepregs. The percentage void volume for all laminates was determined by the acid digestion method. For the MR50/LTM25 laminates, the average void volume was 2.18 percent, with minimum and maximum values of 1.42 and 3.85 percent, respectively. For the CFS003/LTM25 laminates, the average void volume was 1.45 percent, with minimum and maximum values of 1.21 and 1.82 percent, respectively. These relatively high values of void volume should be considered when interpreting the results presented in this report.

A portion of one of the two batches of MR50/LTM25 prepreg had a 2-4 inch wide imperfection along the middle of the prepreg tape. This imperfection seemed to be caused by a change in the fiber or resin concentration. This peculiarity in the material was visible in the ultrasonic inspection of the laminates.

4.0 Specimen Conditioning

Specimen conditioning was performed both at Northrop Grumman Corp. and NASA LaRC. Two slightly different conditioning procedures were used depending on where conditioning took place. Both procedures are described below. Mechanical and bolt bearing properties tests were performed on specimens using the Northrop Grumman Corp. conditioning procedure. Open-hole compression (OHC), open-hole tension (OHT), and compression-after-impact (CAI) tests were performed on specimens using the NASA LaRC conditioning procedure.

Northrop Grumman Corp. Conditioning Procedure

All test specimens were dried in a vacuum oven for 5 days at 160°F. After drying, specimens to be tested in the CTD and RTD conditions were stored at 0°F in moisture-proof bags until testing was performed. Specimens to be tested in the ETW condition were moisture conditioned in a humidity chamber at 160°F and 98% relative humidity until the moisture content remained approximately unchanged. For all tests except bolt bearing, the moisture content was approximately 0.83% and 1.05% for MR50/LTM25 and CFS003/LTM25, respectively. For bolt bearing tests, the moisture content was 1.19% and 1.20% for MR50/LTM25 and CFS003/LTM25, respectively. After moisture conditioning, specimens to be tested in the ETW condition were stored at 0°F in moisture-proof bags until testing was performed.

NASA LaRC Conditioning Procedure

Properties of specimens in the CTD, ETD, and RTD conditions were obtained by testing them in the as-cured condition. Specimens to be tested in the RTW and ETW conditions were moisture conditioned by full immersion in water at 160°F for 123 days. The moisture content was 1.72% and 2.03% for MR50/LTM25 and CFS003/LTM25, respectively. These moisture content numbers assume that the as-cured condition had 0% moisture content. Specimens that were moisture conditioned were tested within 72 hours of removal from the conditioning chamber.

5.0 Testing

The test procedures used to determine the mechanical properties are listed in Table 4. The test procedures used to determine the structural properties are listed in Table 5. For both the mechanical and structural properties, some deviations were made from the standard test procedures; most notably in the data reduction. See references 2 and 3 for descriptions of some of these deviations. Fiber volume fractions were determined using the acid digestion method. Glass transition temperatures were determined using the Northrop Grumman Corp. B2 Division process specification T-139A† . The cold and elevated temperatures used for testing were -125°F and 180°F, respectively.

6.0 Test Results

Results of the testing are shown in Tables 6 through 13. For the mechanical and the bolt bearing properties, most results are the average of data from six specimens. For the OHC, OHT, and CAI properties, most results are the average of data from three specimens. However, due to the loss of some specimens (either due to testing or instrumentation failure), some results are the average of data from fewer specimens. The number of data points used to calculate a particular property is given in the tables.

Normalization of fiber dominated mechanical properties was performed with respect to the measured ply thickness. The nominal ply thickness was determined by averaging all the ply thicknesses of specimens used to determine mechanical properties for each material form. The normalized values were calculated by the equation

$$\text{Normalized Value} = (\text{Measured Value}) \times \frac{\text{Specimen Thickness}}{\text{Nominal Thickness}}$$

where the "Nominal Thickness" is the nominal ply thickness times the number of plies in the laminate.

The mechanical, structural, and additional properties of MR50/LTM25 are shown in Tables 6 through 9. Tables 6 and 7 present the mechanical properties. Table 8 presents the structural properties. Table 9 presents the additional properties listed in Table 2.

The mechanical, structural, and additional properties of CFS003/LTM25 are shown in Tables 10 through 13. Tables 10 and 11 present the mechanical properties. Table 12 presents the structural properties. Table 13 presents the additional properties listed in Table 2.

† Process specification T-139A is proprietary to the Northrop Grumman Corp. Thus, this process specification is not publicly available and no reference can be given.

References

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3) Shah, C. H.; and Postyn, A. S.: *Pin Bearing Evaluation of LTM25 Composite Materials*. NASA CR-201596, 1996.

4) Anon.: Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials, ASTM D3039, *1994 Annual Book of ASTM Standards*, Vol. 15.03, American Society for Testing and Materials, 1994, pp. 115-124.

5) Anon.: Standard Test Method for Compressive Properties of Rigid Plastics, D695, *1996 Annual Book of ASTM Standards*, Vol. 8.01, American Society for Testing and Materials, 1996, pp. 82-88.

6) Anon.: Standard Practice for In-Plane Shear Stress-Strain Response of Unidirectional Polymer Matrix Composites, ASTM D3518, *1994 Annual Book of ASTM Standards*, Vol. 15.03, American Society for Testing and Materials, 1994, pp. 145-149.

7) Anon.: Polymer Matrix Composites—Vol. 1: Guidelines, MIL-HDBK-17-1D, U.S. Department of Defense, February 1994, pp. 7-5 - 7-9.

8) ACEE Composites Project Office: *NASA/Aircraft Industry Standard Specification for Graphite Fiber/Toughened Thermoset Resin Composite Material*, NASA RP-1142, 1985.

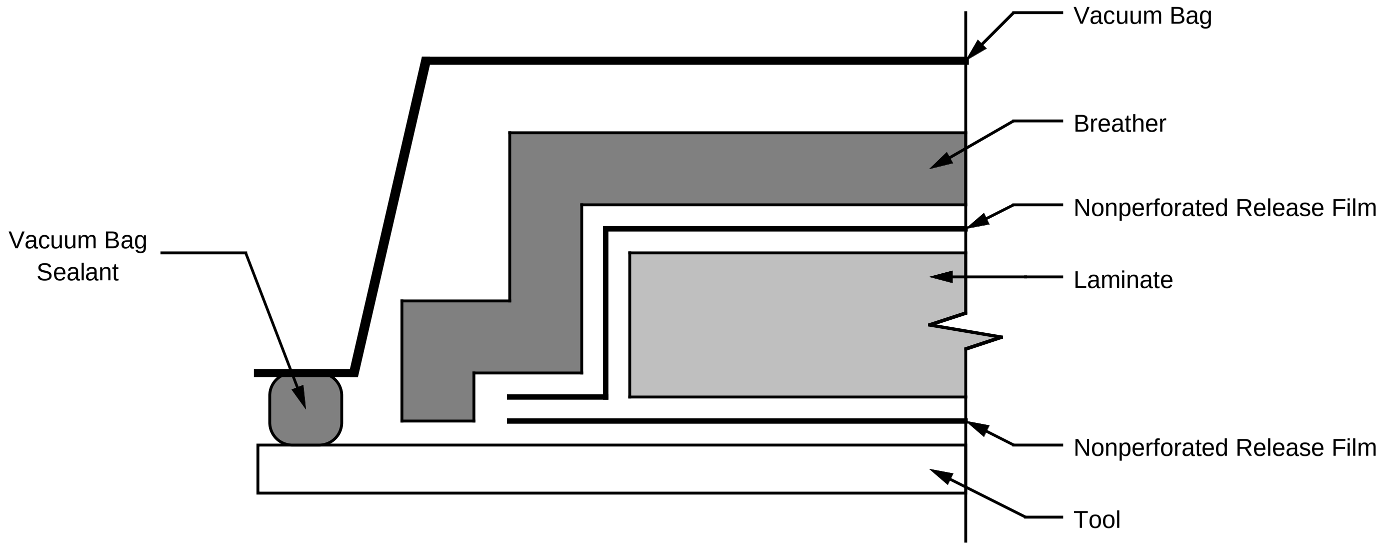

Figure 1. Laminate Bagging Layout

Table 1. Mechanical Properties Reported

Property	Description
E_1^t	Longitudinal modulus, tension
E_1^c	Longitudinal modulus, compression
E_2^t	Transverse modulus, tension
E_2^c	Transverse modulus, compression
G_{12}^s	In-plane shear modulus
ν_{12}^t	Major Poisson's ratio, tension
ν_{12}^c	Major Poisson's ratio, compression
ν_{21}^t	Minor Poisson's ratio, tension
ν_{21}^c	Minor Poisson's ratio, compression
F_1^{tu}	Longitudinal ultimate stress, tension
F_1^{cu}	Longitudinal ultimate stress, compression
F_2^{tu}	Transverse ultimate stress, tension
F_2^{cu}	Transverse ultimate stress, compression
F_{12}^{su}	In-plane shear ultimate stress
ε_1^{tu}	Longitudinal ultimate strain, tension
ε_1^{cu}	Longitudinal ultimate strain, compression
ε_2^{tu}	Transverse ultimate strain, tension
ε_2^{cu}	Transverse ultimate strain, compression
γ_{12}^{su}	In-plane shear ultimate strain

Note: All these properties are reported for the CTD, RTD, and ETW conditions.

Table 2. Structural Properties Reported

Property	Description	Conditions
F_p^{br}	Bolt bearing proportional limit stress	CTD, RTD, ETW
F_y^{br}	Bolt bearing yield stress	CTD, RTD, ETW
F_u^{br}	Bolt bearing ultimate stress	CTD, RTD, ETW
F_u^{ohc}	Open-hole compression ultimate stress	RTD, RTW, ETD, ETW
F_u^{oht}	Open-hole tension ultimate stress	CTD, RTD
F_u^{cai}	Compression-after-impact ultimate stress	RTD
ε_u^{cai}	Compression-after-impact ultimate strain	RTD

Table 3. Additional Properties Reported

Property	Description
ρ	Material density
V_f	Fiber volume fraction
t_{nom}	Nominal ply thickness
T_g^{dry}	Glass transition temperature, dry
T_g^{wet}	Glass transition temperature, wet
M_g	Moisture gain from the dry to the wet condition
α_1	Longitudinal coefficient of thermal expansion at room temperature
α_2	Transverse coefficient of thermal expansion at room temperature

Table 4. Test Procedures for Mechanical Properties

Property	**Test Procedure**†
E_1^t	ASTM D3039
E_1^c	ASTM D695
E_2^t	ASTM D3039
E_2^c	NAI-1504, Rev. C or ASTM D695‡
G_{12}^s	ASTM D3518
ν_{12}^t	ASTM D3039
ν_{12}^c	ASTM D695
ν_{21}^t	ASTM D3039
ν_{21}^c	NAI-1504, Rev. C or ASTM D695‡
F_1^{tu}	ASTM D3039
F_1^{cu}	ASTM D695
F_2^{tu}	ASTM D3039
F_2^{cu}	NAI-1504, Rev. C or ASTM D695‡
F_{12}^{su}	ASTM D3518
ε_1^{tu}	ASTM D3039
ε_1^{cu}	ASTM D695
ε_2^{tu}	ASTM D3039
ε_2^{cu}	NAI-1504, Rev. C or ASTM D695‡
γ_{12}^{su}	ASTM D3518

†Complete references for the ASTM test procedures are given in the References section of this report. The NAI-1504, Rev. C test procedure is proprietary to the Northrop Grumman Corp. Thus, this test procedure is not publicly available and no reference can be given. See Section 5 of this report for additional remarks on the test procedures.

‡For the MR50/LTM25 (unidirectional) material, the 3-in by 1-in compression test specimen described in Northrop Grumman Corp. material specification NAI-1504, Rev. C, was used. For the CFS003/LTM25 (fabric) material, the ASTM D695 test procedure was used.

Table 5. Test Procedures for Structural Properties

Property	**Test Procedure**†
F_p^{br}	MIL-HDBK-17-1D
F_y^{br}	MIL-HDBK-17-1D
F_u^{br}	MIL-HDBK-17-1D
F_u^{ohc}	NASA RP-1142‡
F_u^{oht}	NASA RP-1142‡
F_u^{cai}	NASA RP-1142‡
ε_u^{cai}	NASA RP-1142‡

†Complete references for these test procedures are given in the References section of this report. See Section 5 of this report for additional remarks on the test procedures.

‡The test procedures specified in NASA RP-1142 are intended to be used with unidirectional materials. In the present work, the same test procedures were used for the CFS003/LTM25 fabric material, except that the laminates used were $[45/0/-45/90]_{2S}$ for the OHC and OHT tests, and $[45/0/-45/90]_{4S}$ for the CAI tests. In addition, the cold and elevated temperatures used in the present work were -125°F and 180°F, respectively, instead of those specified in NASA RP-1142.

Table 6. Measured Mechanical Properties for MR50/LTM25

Property†		CTD	RTD	ETW
E_1^t (Msi)	Mean	20.7 (6)	21.6 (6)	20.7 (6)
	Minimum	20.1	20.2	18.7
	Maximum	22.0	22.8	22.3
	Coef. of Variation (%)	3.83	4.14	5.66
ν_{12}^t	Mean	0.374 (6)	0.345 (6)	0.359 (6)
	Minimum	0.335	0.264	0.321
	Maximum	0.463	0.387	0.427
	Coef. of Variation (%)	12.9	14.1	11.2
E_1^c (Msi)	Mean	22.2 (6)	22.3 (6)	22.3 (6)
	Minimum	21.0	21.3	21.4
	Maximum	23.4	23.6	23.8
	Coef. of Variation (%)	4.07	4.58	3.52
ν_{12}^c	Mean	0.364 (6)	0.366 (6)	0.431 (6)
	Minimum	0.344	0.330	0.361
	Maximum	0.422	0.395	0.520
	Coef. of Variation (%)	8.07	7.13	12.4
E_2^t (Msi)	Mean	1.33 (6)	1.06 (6)	0.86 (6)
	Minimum	1.28	1.03	0.81
	Maximum	1.37	1.09	1.00
	Coef. of Variation (%)	2.73	2.44	8.24
ν_{21}^t	Mean	0.052 (6)	0.028 (6)	0.101 (6)
	Minimum	0.049	0.020	0.036
	Maximum	0.056	0.042	0.263
	Coef. of Variation (%)	4.79	36.6	89.0
E_2^c (Msi)	Mean	1.55 (6)	1.21 (6)	0.96 (6)
	Minimum	1.35	1.10	0.85
	Maximum	1.92	1.35	1.09
	Coef. of Variation (%)	13.1	7.90	10.6
ν_{21}^c	Mean	0.029 (6)	0.011 (4)	0.012 (5)
	Minimum	0.024	0.010	0.007
	Maximum	0.035	0.013	0.023
	Coef. of Variation (%)	18.2	11.2	56.1
G_{12}^s (Msi)	Mean	0.734 (6)	0.608 (6)	0.351 (6)
	Minimum	0.706	0.584	0.333
	Maximum	0.749	0.629	0.366
	Coef. of Variation (%)	2.12	2.48	3.35

†The numbers in parentheses next to the mean values in this Table indicate how many data points were used to calculate the particular property.

Table 6. Measured Mechanical Properties for MR50/LTM25 - Concluded

Property[†]		CTD	RTD	ETW
F_1^{tu} (ksi)	Mean	279 (6)	280 (6)	268 (6)
	Minimum	250	262	242
	Maximum	310	293	283
	Coef. of Variation (%)	7.07	4.55	5.72
F_1^{cu} (ksi)	Mean	216 (6)	171 (6)	113 (6)
	Minimum	195	149	94.0
	Maximum	236	196	126
	Coef. of Variation (%)	6.14	8.90	10.2
F_2^{tu} (ksi)	Mean	4.37 (6)	2.97 (6)	1.90 (6)
	Minimum	3.54	2.60	1.77
	Maximum	5.19	3.39	2.01
	Coef. of Variation (%)	12.5	10.9	4.36
F_2^{cu} (ksi)	Mean	34.7 (6)	21.1 (6)	10.8 (6)
	Minimum	32.0	20.0	9.85
	Maximum	36.8	22.1	11.9
	Coef. of Variation (%)	6.09	3.74	7.51
F_{12}^{su} (ksi)	Mean	16.1 (6)	12.9 (6)	7.33 (6)
	Minimum	15.4	12.6	7.27
	Maximum	16.6	13.2	7.46
	Coef. of Variation (%)	2.80	1.56	0.94
ε_1^{tu} (μin/in)	Mean	11,600 (6)	11,800 (6)	13,000 (6)
	Minimum	10,700	11,300	11,400
	Maximum	12,600	12,200	14,300
	Coef. of Variation (%)	5.61	2.49	8.08
ε_1^{cu} (μin/in)	Mean	9,740 (6)	7,660 (6)	5,080 (6)
	Minimum	8,790	6,670	4,240
	Maximum	10,600	8,780	5,640
	Coef. of Variation (%)	6.14	8.90	10.2
ε_2^{tu} (μin/in)	Mean	3,250 (6)	2,900 (6)	2,310 (6)
	Minimum	2,660	2,440	2,000
	Maximum	3,830	3,350	2,600
	Coef. of Variation (%)	12.5	10.9	8.67
ε_2^{cu} (μin/in)	Mean	22,600 (6)	25,200 (6)	25,300 (5)
	Minimum	18,500	22,700	21,500
	Maximum	27,200	28,300	28,300
	Coef. of Variation (%)	14.9	7.97	11.6
γ_{12}^{su} (μin/in)	Mean	22,000 (6)	21,300 (6)	20,900 (6)
	Minimum	21,100	20,900	19,900
	Maximum	22,500	22,100	22,400
	Coef. of Variation (%)	2.32	2.05	4.22

[†]The numbers in parentheses next to the mean values in this Table indicate how many data points were used to calculate the particular property.

Table 7. Normalized Mechanical Properties for MR50/LTM25

Property†		**CTD**	**RTD**	**ETW**
E_1^t (Msi)	Mean	20.9 (6)	22.6 (6)	21.4 (6)
	Minimum	20.2	21.4	20.5
	Maximum	22.1	23.8	22.4
	Coef. of Variation (%)	3.53	3.34	3.44
E_1^c (Msi)	Mean	21.0 (6)	21.7 (6)	21.7 (6)
	Minimum	20.0	21.1	21.1
	Maximum	22.3	22.5	22.3
	Coef. of Variation (%)	4.38	2.40	1.94
F_1^{tu} (ksi)	Mean	283 (6)	293 (6)	277 (6)
	Minimum	252	278	248
	Maximum	312	305	287
	Coef. of Variation (%)	6.99	3.76	5.30
F_1^{cu} (ksi)	Mean	206 (6)	165 (6)	107 (6)
	Minimum	190	144	89.8
	Maximum	225	183	118
	Coef. of Variation (%)	5.62	7.53	9.82

†The numbers in parentheses next to the mean values in this Table indicate how many data points were used to calculate the particular property.

Table 8. Structural Properties for MR50/LTM25

Property†		CTD	RTD	RTW	ETD	ETW
F_p^{br} (ksi)	Mean	77.4 (6)	58.3 (6)			31.4 (6)
	Minimum	70.7	54.2			26.9
	Maximum	82.3	62.7			35.4
	Coef. of Variation (%)	5.20	5.58			10.2
F_y^{br} (ksi)	Mean	92.3 (6)	72.4 (6)			50.0 (6)
	Minimum	85.9	62.6			44.9
	Maximum	100	81.5			53.3
	Coef. of Variation (%)	5.62	9.71			6.34
F_u^{br} (ksi)	Mean	176 (6)	143 (6)			109 (6)
	Minimum	171	132			101
	Maximum	184	154			119
	Coef. of Variation (%)	2.71	4.97			6.37
F_u^{ohc} (ksi)	Mean		36.4 (3)	34.2 (3)	31.4 (3)	17.9 (2)
	Minimum		34.5	33.3	30.3	17.3
	Maximum		38.0	35.6	32.3	18.5
	Coef. of Variation (%)		4.86	3.53	3.23	4.74
F_u^{oht} (ksi)	Mean	56.8 (3)	64.0 (3)			
	Minimum	55.8	61.5			
	Maximum	57.7	66.9			
	Coef. of Variation (%)	1.67	4.27			
F_u^{cai} (ksi)	Mean		26.7 (2)			
	Minimum		26.4			
	Maximum		26.9			
	Coef. of Variation (%)		1.33			
ε_u^{cai} (μin/in)	Mean		3,370 (2)			
	Minimum		3,330			
	Maximum		3,400			
	Coef. of Variation (%)		1.47			

†The numbers in parentheses next to the mean values in this Table indicates how many data points were used to calculate the particular property.

Table 9. Additional Properties for MR50/LTM25

Property	**Results**
ρ	0.0551 lb/in^3
V_f	60.9%
t_{nom}	0.00576 in
T_g^{dry}	265°F†
T_g^{wet}	218°F†
M_g	1.72%‡
α_1	-0.24 μin/in/°F
α_2	20.8 μin/in/°F

†Specimens tested for T_g^{dry} were dried using the Northrop Grumman Corp. conditioning procedure. Specimens tested for T_g^{wet} were conditioned to approximately 0.83% moisture content using the Northrop Grumman conditioning procedure. See Section 4.0.

‡Specimens tested for this property were conditioned using the NASA LaRC conditioning procedure. See Section 4.0.

Table 10. Measured Mechanical Properties for CFS003/LTM25

Property†		CTD	RTD	ETW
E_1^t (Msi)	Mean	7.57 (6)	7.06 (6)	6.48 (6)
	Minimum	6.99	6.76	6.05
	Maximum	7.80	7.35	6.86
	Coef. of Variation (%)	4.15	2.88	4.54
ν_{12}^t	Mean	0.065 (5)	0.042 (6)	0.167 (3)
	Minimum	0.017	0.029	0.140
	Maximum	0.116	0.054	0.184
	Coef. of Variation (%)	56.0	22.5	14.3
E_1^c (Msi)	Mean	7.46 (6)	7.20 (6)	8.37 (6)
	Minimum	6.66	6.69	7.85
	Maximum	8.74	7.81	9.28
	Coef. of Variation (%)	10.5	5.74	5.94
ν_{12}^c	Mean	0.076 (6)	0.033 (5)	0.051 (5)
	Minimum	0.050	0.011	0.014
	Maximum	0.100	0.079	0.076
	Coef. of Variation (%)	22.7	84.5	51.5
E_2^t (Msi)	Mean	7.58 (6)	7.52 (6)	6.11 (6)
	Minimum	7.27	7.02	4.61
	Maximum	8.02	7.88	7.85
	Coef. of Variation (%)	3.90	5.13	19.3
ν_{21}^t	Mean	0.094 (5)	0.028 (6)	0.041 (5)
	Minimum	0.070	0.009	0.009
	Maximum	0.106	0.059	0.079
	Coef. of Variation (%)	14.0	64.8	61.7
E_2^c (Msi)	Mean	7.84 (6)	7.54 (6)	7.22 (6)
	Minimum	7.43	7.39	6.96
	Maximum	8.10	7.67	7.63
	Coef. of Variation (%)	3.63	1.44	3.39
ν_{21}^c	Mean	0.068 (6)	0.035 (3)	0.023 (2)
	Minimum	0.060	0.011	0.017
	Maximum	0.078	0.063	0.029
	Coef. of Variation (%)	10.5	74.9	36.9
G_{12}^s (Msi)	Mean	0.587 (6)	0.414 (6)	0.369 (6)
	Minimum	0.576	0.402	0.355
	Maximum	0.598	0.430	0.374
	Coef. of Variation (%)	1.47	2.66	1.88

†The numbers in parentheses next to the mean values in this Table indicate how many data points were used to calculate the particular property.

Table 10. Measured Mechanical Properties for CFS003/LTM25 - Concluded

Property†		CTD	RTD	ETW
F_1^{tu} (ksi)	Mean	76.1 (6)	81.6 (6)	83.4 (6)
	Minimum	67.7	71.5	78.4
	Maximum	82.2	88.2	85.4
	Coef. of Variation (%)	6.45	7.88	3.09
F_1^{cu} (ksi)	Mean	113 (6)	93.1 (6)	55.1 (6)
	Minimum	108	89.5	49.0
	Maximum	116	98.1	60.0
	Coef. of Variation (%)	3.01	3.50	7.65
F_2^{tu} (ksi)	Mean	79.9 (6)	88.8 (6)	85.0 (6)
	Minimum	71.3	85.0	82.7
	Maximum	87.4	91.3	86.5
	Coef. of Variation (%)	6.56	2.54	1.73
F_2^{cu} (ksi)	Mean	100 (6)	81.7 (6)	54.0 (6)
	Minimum	93.3	74.1	50.8
	Maximum	105	90.3	60.0
	Coef. of Variation (%)	4.39	7.69	6.32
F_{12}^{su} (ksi)	Mean	14.2 (6)	12.2 (6)	7.71 (6)
	Minimum	13.5	12.0	7.61
	Maximum	14.5	12.4	7.86
	Coef. of Variation (%)	2.60	1.49	1.12
ε_1^{tu} (μin/in)	Mean	10,000 (6)	11,100 (6)	12,600 (6)
	Minimum	8,500	9,550	11,500
	Maximum	10,800	11,800	13,700
	Coef. of Variation (%)	8.85	7.84	7.64
ε_1^{cu} (μin/in)	Mean	15,100 (6)	12,900 (6)	6,580 (6)
	Minimum	14,500	12,400	5,860
	Maximum	15,500	13,600	7,170
	Coef. of Variation (%)	3.01	3.50	7.65
ε_2^{tu} (μin/in)	Mean	10,500 (6)	11,400 (6)	14,400 (6)
	Minimum	9,730	10,700	10,500
	Maximum	11,100	12,800	18,200
	Coef. of Variation (%)	5.12	6.81	19.3
ε_2^{cu} (μin/in)	Mean	12,800 (6)	10,800 (6)	7,490 (6)
	Minimum	11,900	9,830	7,030
	Maximum	13,400	12,000	8,320
	Coef. of Variation (%)	4.39	7.69	6.32
γ_{12}^{su} (μin/in)	Mean	24,100 (6)	29,600 (6)	20,900 (6)
	Minimum	22,700	28,800	20,400
	Maximum	25,100	30,200	21,700
	Coef. of Variation (%)	3.74	1.77	2.32

†The numbers in parentheses next to the mean values in this Table indicate how many data points were used to calculate the particular property.

Table 11. Normalized Mechanical Properties for CFS003/LTM25

Property†		CTD	RTD	ETW
E_1^t (Msi)	Mean	7.93 (6)	7.77 (6)	6.74 (6)
	Minimum	7.44	7.48	6.19
	Maximum	8.20	8.13	7.30
	Coef. of Variation (%)	3.31	2.73	5.95
E_1^c (Msi)	Mean	7.08 (6)	6.84 (6)	7.97 (6)
	Minimum	6.45	6.29	7.49
	Maximum	8.22	7.45	8.85
	Coef. of Variation (%)	9.58	6.04	5.84
E_2^t (Msi)	Mean	7.83 (6)	8.00 (6)	6.26 (6)
	Minimum	7.31	7.60	4.72
	Maximum	8.32	8.28	7.93
	Coef. of Variation (%)	4.78	3.76	19.2
E_2^c (Msi)	Mean	7.34 (6)	7.05 (6)	6.77 (6)
	Minimum	6.99	6.95	6.53
	Maximum	7.62	7.20	7.18
	Coef. of Variation (%)	3.36	1.26	3.64
F_1^{tu} (ksi)	Mean	79.8 (6)	89.7 (6)	86.7 (6)
	Minimum	70.3	79.1	81.3
	Maximum	84.8	95.2	89.4
	Coef. of Variation (%)	6.50	7.24	3.64
F_1^{cu} (ksi)	Mean	113 (6)	93.2 (6)	54.3 (6)
	Minimum	108	89.8	48.1
	Maximum	115	97.7	58.9
	Coef. of Variation (%)	2.78	3.17	7.55
F_2^{tu} (ksi)	Mean	82.5 (6)	94.6 (6)	87.2 (6)
	Minimum	74.0	91.7	83.5
	Maximum	90.6	98.2	89.6
	Coef. of Variation (%)	6.88	2.60	2.53
F_2^{cu} (ksi)	Mean	98.7 (6)	80.6 (6)	52.1 (6)
	Minimum	90.3	72.8	49.1
	Maximum	105	89.9	57.3
	Coef. of Variation (%)	5.50	8.39	5.97

†The numbers in parentheses next to the mean values in this Table indicate how many data points were used to calculate the particular property.

Table 12. Structural Properties for CFS003/LTM25

Property†		CTD	RTD	RTW	ETD	ETW
F_p^{br} (ksi)	Mean	82.6 (6)	66.7 (6)			40.8 (6)
	Minimum	74.3	59.1			37.1
	Maximum	90.4	71.2			45.3
	Coef. of Variation (%)	7.60	6.27			7.54
F_y^{br} (ksi)	Mean	93.5 (6)	61.1 (5)			53.8 (6)
	Minimum	83.3	57.0			50.8
	Maximum	106	66.7			59.1
	Coef. of Variation (%)	9.36	5.85			5.59
F_u^{br} (ksi)	Mean	131 (6)	89.3 (5)			93.6 (6)
	Minimum	129	86.5			90.8
	Maximum	133	94.5			99.4
	Coef. of Variation (%)	1.43	3.41			3.29
F_u^{ohc} (ksi)	Mean		34.1 (3)	32.1 (3)	26.5 (3)	16.8 (1)
	Minimum		33.8	31.8	26.0	-
	Maximum		34.6	32.5	27.1	-
	Coef. of Variation (%)		1.22	1.09	2.15	-
F_u^{oht} (ksi)	Mean	33.7 (3)	36.3 (3)			
	Minimum	32.5	35.5			
	Maximum	34.4	36.8			
	Coef. of Variation (%)	3.18	1.88			
F_u^{cai} (ksi)	Mean		31.5 (3)			
	Minimum		29.9			
	Maximum		32.5			
	Coef. of Variation (%)		4.38			
ε_u^{cai} (μin/in)	Mean		6,610 (3)			
	Minimum		6,260			
	Maximum		6,790			
	Coef. of Variation (%)		4.48			

†The numbers in parentheses next to the mean values in this Table indicates how many data points were used to calculate the particular property.

Table 13. Additional Properties for CFS003/LTM25

Property	**Results**
ρ	0.0525 lb/in^3
V_f	46.9%
t_{nom}	0.00904 in
T_g^{dry}	268°F†
T_g^{wet}	225°F†
M_g	2.03%‡
α_1	2.13 μin/in/°F
α_2	2.11 μin/in/°F

†Specimens tested for T_g^{dry} were dried using the Northrop Grumman Corp. conditioning procedure. Specimens tested for T_g^{wet} were conditioned to approximately 1.05% moisture content using the Northrop Grumman Corp. conditioning procedure. See Section 4.0.

‡Specimens tested for this property were conditioned using the NASA LaRC conditioning procedure. See Section 4.0.